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CARBON DYNAMICS IN CHANGING HYDROLOGIC REGIMES

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SUMMARY

The goal of the research is to understand the interactions between the carbon and water cycles and to improve predictive modeling of the co-evolution of climate and the carbon cycle.

MAJOR ACCOMPLISHMENTS

1. CO_2 fertilization and streamflow

The 4th Assessment Report of the IPCC includes results from the first generation of coupled carbon-climate models (Brasseur and Denman 2007). Our analysis of the models' results from the coupled carbon-climate model experiments reveals that the divergence in multi-model results for the 21st century can be traced to three factors in the carbon-climate models: the CO_2 fertilization factor (fractional increase in NPP for a doubling of CO_2); the soil carbon turnover time; and ecosystem response to droughts.

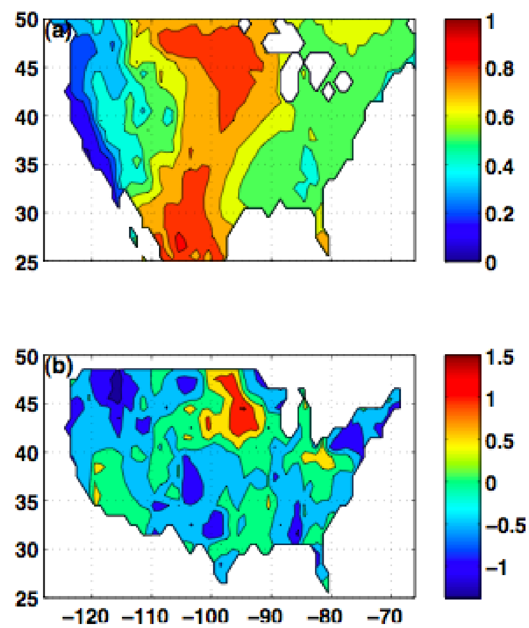

Figure 1. (a) Fraction of precipitation that falls in the summer. (b) Apparent response of streamflow to GHG warming (SD per 100 ppmv CO_2). From Krakauer and Fung (2008).

CO_2 fertilization of photosynthesis could reduce transpiration and enhance streamflow. While streamflow is increasing globally, there is controversy over whether the streamflow increases as a result of CO_2 fertilization (Gedney et al. 2006) or of landuse modification (Piao et al. 2007). We have found evidence for CO_2 fertilization in the upper mid-west of the US in our analysis of streamflow data in "undisturbed" watersheds of the US (Krakauer and Fung 2008). The hypothesis for the analysis is that variability in streamflow provides a cross-check on evapotranspiration, after variability in precipitation has been accounted for. The residuals in streamflow (after regression with precipitation) show a positive correlation with CO_2 only in the upper Great Plains (Figure 1). This is a region of C3 grasslands, which respond rapidly to changes in CO_2 concentrations. In other regions of the US, the negative correlation with CO_2 is mostly likely due to increasing evaporation and hence decreasing streamflow with temperature. Changes in transpiration, except in the C3 grasslands, cannot be extracted from the analysis.

In the same streamflow analysis, we show that information about evapotranspiration, which is very difficult to quantify on watershed to continental scale, can be inferred as the intercept in the regression of streamflow against precipitation. In regions of summer rain, the intercept (zero streamflow) is 79% of mean annual precipitation, suggesting that the ecosystems recycle most of the rainfall. In winter-rain regions, however, the intercept is only 17% of the mean annual precipitation. Because the NPP in winter-rain regions are not smaller than that in summer rain regions by a factor of 5, this small fraction re-iterates the importance of subsurface storage of moisture to sustain ecosystem function. A new hypothesis that emerges from the analysis is that the intercept gives the minimum annual precipitation for ecosystem survival. This hypothesis will be pursued further using AmeriFlux data in the coming period.

2. Transpiration-ice albedo feedback

The range of high-latitude trees is expected to expand poleward with warming and, in fact, the northern tree-line is moving northward now (e.g. Lloyd, 2005). Changes in vegetation cover are recognized to modify climate and the energy budget of the Earth, through changes in albedo in high latitudes and evapotranspiration (ET) in the tropics (Bonan, 2008; Fischlin et al., 2007). In snow-covered regions, the springtime growth of leaves enhances solar absorption because surface albedo is reduced from the albedo of snow (~0.8) towards the albedo of leaves (~0.1). Leaves also play a hydrologic role, moving water from the soil to the atmosphere through transpiration. Deciduous trees have higher rates of transpiration than needle-leaved trees (e.g. Chapin et al. 2000), and may invade warming tundra more effectively than Boreal evergreen trees (Edwards et al., 2005).

We used the NCAR global climate model (CAM3.0+LSM3.5) with an interactive biosphere (CASA') to investigate the effects of adding deciduous trees on bare ground at high northern latitudes. Four experiments are run – with two representations of vegetation cover (control or modified vegetation), and with two representations of the Arctic ocean boundary condition (fixed SST and sea ice or a slab ocean model). The fixed SST and sea ice experiments focus on atmosphere-land coupling only, while the slab ocean model experiments allow feedbacks between high-latitude land and the Arctic ocean. Albedo change is considered to be the dominant mechanism by which trees directly modify climate at high latitudes (e.g. Bonan et al. 1992). In contrast, we find that the top-of-atmosphere radiative imbalance from enhanced transpiration (associated with the expanded forest cover) is 2.4 times larger than the forcing due to albedo change from the forest. Furthermore, the greenhouse warming by additional water vapor melts sea ice and triggers a positive feedback through changes in ocean albedo and evaporation. Vegetation feedbacks through albedo and transpiration produce a strong warming if they act in combination with sea-ice processes.

Our study does not support the conventional wisdom (e.g. Fischlin et al. 2007) that land albedo is the dominant means by which plants interact with climate at high-northern latitudes. We instead find that expansion of deciduous trees in the Arctic modifies both the short-wave and long-wave energy budgets, and initiates additional positive feedbacks associated with decreased sea-ice albedo and enhanced evaporation. The Arctic ocean feedbacks in turn amplify the warming on land and lead to further albedo decrease and ET increase. The long wave effects from changes in atmospheric moisture are not generally considered in studies of high latitude vegetation change, but we find the direct long wave forcing from water vapor to be larger than the short wave forcing from albedo, and the total response from both ocean and atmosphere to be 2.4 times the direct forcing from albedo alone.

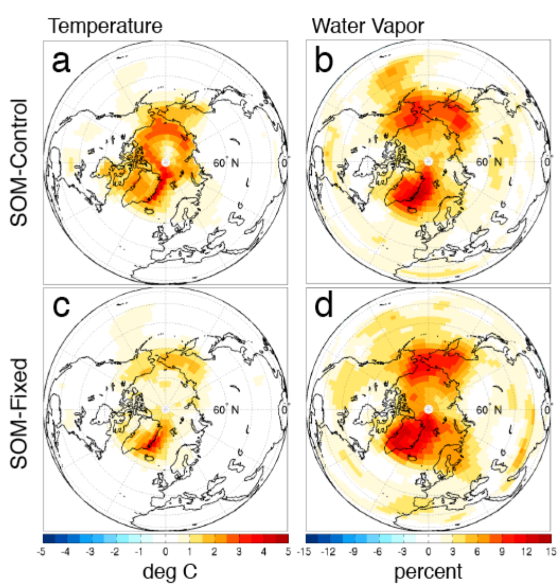

Fig. 2. (A) The difference (SOM-Control) in near surface atmospheric temperature in Kelvin between a model experiment where trees are introduced on bare ground north of 60°N and a corresponding control run with no added trees. **(B)** The same as (A) for column water vapor in percent. **(C)** The difference (SOM-Fixed) in near surface atmospheric temperature in Kelvin between two model experiments where trees are introduced on bare ground north of 60°N, one with one with an interactive slab ocean model (SOM) and the other with fixed sea surface temperatures and sea ice (Fixed). **(D)** The same as (C) for column water vapor in percent.

3. A new contemporary CO_2 budget

We have continued a new inversion for the contemporary carbon budget for the recent decade. The central impetus is the shift of peak fossil fuel CO_2 emission from mid-

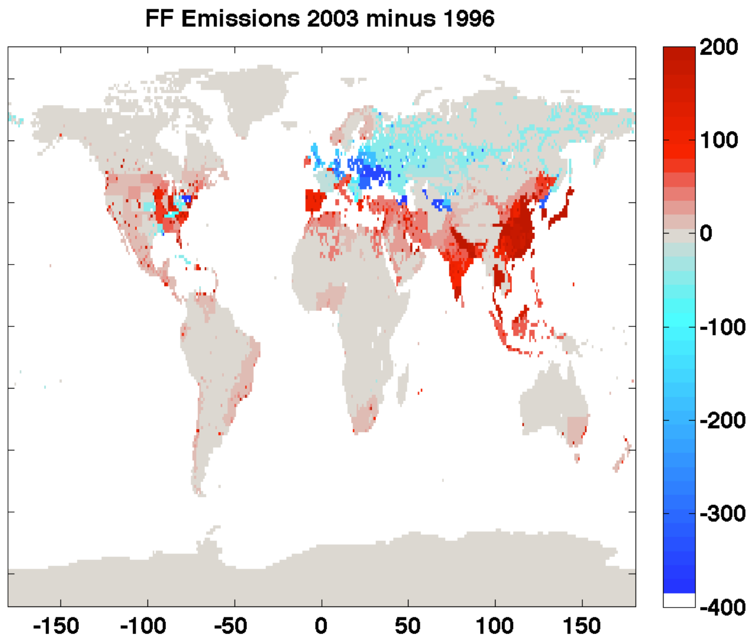

Figure 3. Difference in fossil fuel emission between 1996 and 2003 showing the shift of emissions to the subtropics. The global annual emissions are 6.65 and 7.50 PgC/yr for 1996 and 2003, respectively. Unit is gC/m^2/yr

latitudes to the subtropics with the emergence of China and India as major emitters (Figure 3).

We started with a global 3D atmospheric tracer transport model calculation of the distribution of an inert mid-latitude "industrial" tracer using atmospheric circulation statistics from the NCEP reanalysis. A surprise is an accelerating interhemispheric transport from 1980 to 2003, and the acceleration may or may not be an artifact of the meteorological data assimilation. The NCEP data assimilation protocol assimilates the data from maximum coverage for each year rather than data across common (and hence minimal) data coverage over the years. Therefore, instead of focusing on the past two decades, we chose to focus on two periods, 1996-1999, and 2000-2003, when the NCEP reanalysis circulation is more stable. Figure 4 shows the shifting of the fossil fuel CO_2 emission pattern from the mid-latitudes to the subtropics, and the resultant atmospheric CO_2 concentration (if 100% airborne). Compared with the observed north-south CO_2 gradients for the same period, it is clear that there is a reduction in the northern hemisphere CO_2 sink.

The challenge of an inhomogeneous observing network creating trend artifacts in the NCEP reanalysis is also present in the atmospheric CO_2 observing network (Figure 5). In particular, there are few CO_2 observations around China. Table 1 illustrates the sensitivity of the inferred latitudinal distribution of the carbon sink for the 2000-2003 period, for the same fossil fuel emissions and same atmospheric circulation statistics.

The "Rodenbeck" network comprises the 35 surface stations, and the "Best 2000" network includes in addition aircraft data, especially the 200mb data from the flight path from Tokyo to Sydney. The sensitivity of the inferred sink, of even the latitudinal

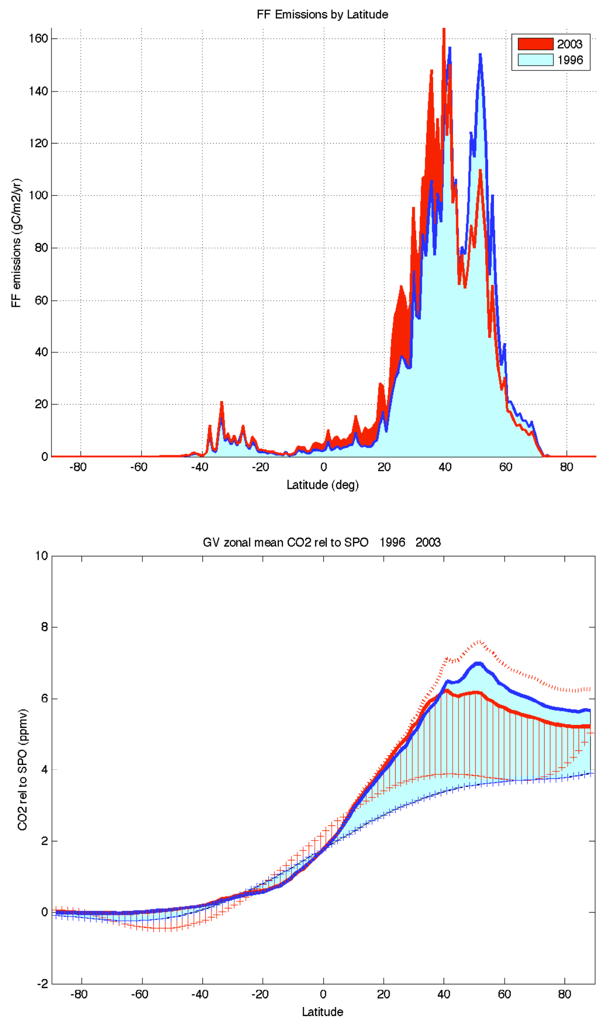

Figure 4. Top: Fossil fuel CO_2 emission for 2003 (red) and 1996 (blue). Bottom: Modeled (thick lines) and observed (crosses) CO_2 gradients for 2003 (red) and 1996 (blue). The hatched area denotes the CO_2 sink required to match the gradient. The dotted red line is the modeled atmospheric CO_2 gradient for 2003 using the circulation statistics of 1996.

distribution of the sinks, to the choice of network is large, ~0.7 PgC/yr in mid-latitudes and close to 1 PgC/yr in the tropics. The sensitivity is comparable to the inferred sink for North America itself.

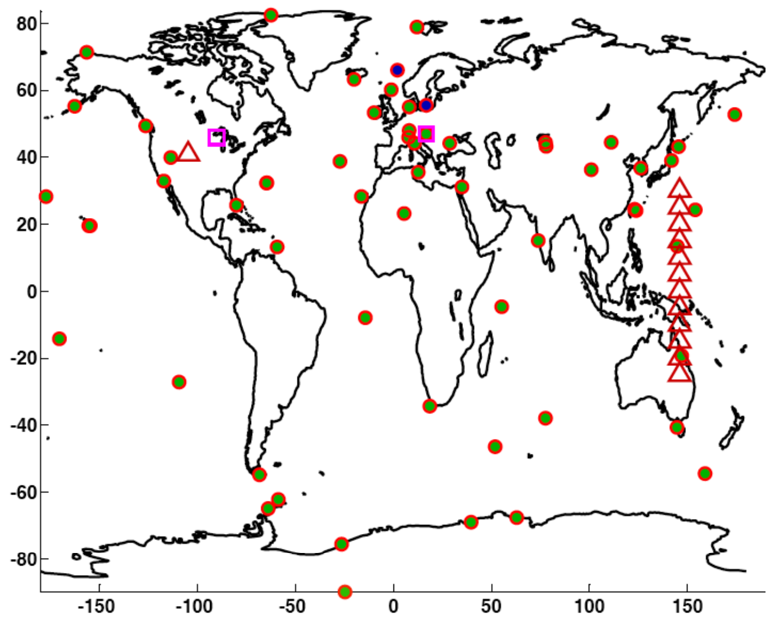

Figure 5. CO_2 observing network for 1996- 2000. Circles are surface sites; squares are flux towers; triangles are aircraft.

Table 1. Sensitivity of CO_2 fluxes (in PgC/yr) averaged for 2000-2003 to choice of observing network.

	"Best 2000"	Rodenbeck 35 stations
15N-90N	-2.5	-3.2
Tropics	1.6	2.5
90S-15S	-1.9	-2.2
Global	-2.9	-2.9

There are few surface observing sites in boreal and temperate Eurasia and tropical Asia; those in China are upwind of the industrial fossil fuel emissions. And so the fluxes in these regions are not well constrained by the data, and there is a tendency for the regional fluxes to "flip" between these poorly constrained regions. The addition of the Tokyo-to-Sydney aircraft data thus constrains the fluxes from tropical Asia, as well as providing data on the vertical profile of CO_2 in this region.

The CO_2 sources and sinks inferred for 1996-1999 and 2000-2003 are shown in Table 2. We have chosen the period firstly because the trend in atmospheric circulation is minimal and the observing network overlap is maximal. More interestingly, the two periods have approximately the same global carbon sink (-2.76 and -2.84 PgC/yr for 1996-9 and 2000-3, respectively), and the regional distribution of the sink is very different because of the shift in fossil fuel emissions.

Table 2. Inferred non-fossil fuel regional CO_2 sources and sinks for 1996-1999 and for 2000-2003. Unit is PgC/yr.

	1996-1999	**2000-2003**
Land: Northern extratropics	-2.18 +/- 0.32	-1.16 +/- 0.32
Ocean: Northern extratropics	-1.41 +/- 0.30	-1.43 +/- 0.31
Land: Tropics	2.41 +/- 0.82	1.29 +/- 0.84
Ocean: Tropics	0.94 +/- 0.46	0.42 +/- 0.47
Land: Southern extratropics	-0.87 +/- 0.72	-0.38 +/- 0.75
Ocean: Southern extratropics	-1.65 +/- 0.34	-1.57 +/- 0.37
Global	-2.76 +/- 0.47	-2.84 +/- 0.49
Land	-0.64 +/- 0.80	-0.26 +/- 0.83
Ocean	-2.12 +/- 0.68	-2.58 +/- 0.71

The largest change in the sink distribution is the shift in the land sink of ~1 PgC/yr from the northern extratropics to the tropics. While the inversion procedure yields the fluxes for 23 regions of the world, uncertainties in the east-west distribution remain large. The inferred flux for North America temperate region is -0.05 +/- 0.24 and +0.04 +/- 0.26 PgC/yr for 1996-9 and 2003-3, respectively. The near neutral flux inferred is consistent with the effects of drought on terrestrial carbon dynamics, which we have reported on previously, and is smaller than the sink strength for 2007, as reported by CarbonTracker. The reduction in sink strength for the 2000-2003 period further supports the prediction of reduced carbon sink in a future drying climate. A new result, a reduction of the net carbon flux from the tropics of as much as 1 PgC/yr remains to be explained. Increasing fires with droughts would yield a trend opposite to that inferred.

FUTURE DIRECTIONS

The research supported by this grant is systematically showing how critically inferred and predicted carbon dynamics depends on the hydrologic status of the system. Our results have yielded quantitative metrics of ecosystem responses to variations in hydrology that could be used for assessing model performance and guiding model development. To further advance modeling of the hydrologic cycle in climate models, we have embarked on an effort to model soil moisture. While the IPCC reports emphasize the uncertainties in model predictions of precipitation, ecosystems respond to soil moisture, the result of the competition between precipitation and evapotranspiration. Our previous results have demonstrated the importance of hydraulic redistribution by deep roots to sequester water at depth, away from evaporative demand of the atmosphere. The deep water reservoir could thus sustain ecosystems through transient droughts and reduce the probability of massive ecosystem die-back and CO_2 release. We have begun a new effort to model the heterogeneity of the sub-surface (from the surface to >10 meters). The treatment of flow through fractured rock is not new in hydrology but is not included in climate models. We are including a variable water table in a ground hydrology model, and representing hydraulic conductivity between the upper soils and the water table as a probability distribution function. At this writing, we are exploring the vertical variations of the hydraulic conductivity that could match streamflow pulses for precipitation events, and have found that the standard hydraulic conductivity as employed in climate models is inadequate.

PUBLICATIONS SUPPORTED BY THIS GRANT

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